

# DEVELOPMENT OF A PROTOCOL FOR ECOEFFICIENT WOOD HARVESTING ON SENSITIVE SITES (ECOWOOD)

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## SOIL INTERACTION MODEL

### APPENDIX REPORT No 2

EVALUATION OF THE WES-METHOD  
IN ASSESSING THE TRAFFICABILITY OF TERRAIN AND THE  
MOBILITY OF FOREST TRACTORS

PART 1

WES MOBILITY MODELS

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## List of Symbols

$\mu_P$	net traction coefficient, drawbar pull coefficient
P	drawbar pull, kN
W	wheel load, kN
$\mu_R$	rolling resistance coefficient, towed force coefficient
$P_R$	rolling resistance, resistance to movement, kN
$\mu_T$	thrust coefficient, (gross) traction coefficient
$r_r$	rolling radius of the wheel, m
Q	wheel torque, kNm
CI	cone index, soil penetration resistance at a certain depth, kPa
b	tyre section width, m
d	tyre diameter, m
$\delta$	tyre deflection, m, generally on hard surface
h	tyre section height, m
RCI	remoulded cone index
m	number of tracking wheels on one side, number of axles
$W_W$	vehicle weight, kN
HG	hard ground resistance coefficient, tyre hysteresis
$W_R$	rated load of tire as defined by the Tire and Rim Association Yearbook
$\mu_{P0}$	pull coefficient
$\mu_{T0}$	thrust coefficient
$N_{CC}$	Freitag Wheel numeric
$G_{CI}$	soil penetration gradient
z	sinkage, m
MMP	mean maximum pressure
$\gamma$	soil density, N/m <sup>3</sup>
N	Terzaghi constant, Figure 4.2
$z_N$	rut depth, m
N	one of the wheel numerics
$z_{RUT}$	rut depth, m
NGP	nominal ground pressure, kPa
S	slip, %
$s_n$	settlement after the n loading cycle, m
$s_1$	settlement after the 1 <sup>st</sup> cycle, m
n	number of cycles
a	repeatedness coefficient, depending on soil properties and load, multipass coefficient
$z_N$	sinkage after pass N, m
$z_1$	first pass sinkage, m
n	number of passes
$z_n$	rut depth, m
m	inverse of multipass coefficient, $m = \frac{1}{a} z$ rut depth after 2 <sup>nd</sup> pass, m
$z_2$	estimated rut depth after 2 <sup>nd</sup> pass without no prior soil disturbance, m
z	rut depth, m

$q$	penetration resistance, kPa
$\alpha$	rolling resistance to rut depth conversion coefficient
$N_{CI}$	wheel numeric
$EGP_{wheel}$	effective ground pressure for a wheeled vehicle, kPa
$d_s$	diameter of a reference wheel, $d_s=1.500$ m
$NGP_i$	nominal ground pressure of wheel, kPa
$EGP_{tracks}$	effective ground pressure for a tracked vehicle, kPa
$P_t$	track plate pitch, m

## Abstract

Over 20 WES mobility models and rut depth models based on wheel numeric are presented. Some tractor multipass and cyclepass models are developed based on literature survey.

**Keywords:** forestry, terrain transport, trafficability, mobility, sinkage, rut depth, penetrometer, ground damage, WES, multipass

## 1. INTRODUCTION

Essential features of the WES-method are presented in the 2nd part of the report. Several semiempirical mobility models have been developed by different authors. This paper presents an overview on these mobility models. Wheel sinkage and rut depth models based on WES-parameters as input variables are also presented. Most of the WES-models have been developed for a single wheel only, but the modelling of the environment/transport interface requires more developed models, which also permit to analyse the influence of tractor and load characteristics on rut depth. Therefore the development of tractor multicycle and multipass models is of first importance. Some multipass and multicycle models have been developed from the available data.

## 2. TERRAIN AND MACHINE PARAMETERS

In WES-method two types of dimensionless<sup>1</sup> parameters are used. The vehicle mobility is described using mobility parameters, and the wheel/soil interaction using wheel numeric, based on wheel characteristics and the CI-value of the soil.

### 2.1 *Mobility parameters*

Even ASAE have definitions for different mobility parameters, there are some difference between the terms and definitions used by different authors.

Pull coefficient, or net traction coefficient, drawbar pull coefficient

$$\mu_P = \frac{P}{W} \quad (2.1)$$

where

$\mu_P$	net traction coefficient, drawbar pull coefficient
P	drawbar pull, kN
W	wheel load, kN

Rolling resistance coefficient, similar or close to towed force coefficient

---

<sup>1</sup> Earlier, and even today in some countries outside SI-system, the length, pressure, force, energy etc were expressed using Imperial units (inches, yards, feet, pounds, calories etc), which made the calculations more complicated. It was rational to arrange the variables so, that the dimensions were neglected

$$\mu_R = \frac{P_R}{W} \quad (2.2)$$

where

$\mu_R$	rolling resistance coefficient, towed force coefficient
$P_R$	rolling resistance, resistance to movement, kN
$W$	wheel load, kN

Thrust coefficient, gross traction coefficient, traction coefficient

$$\mu_T = \frac{Q}{r_r \cdot W} \quad (2.3)$$

where

$\mu_T$	thrust coefficient, (gross) traction coefficient
$r_r$	rolling radius of the wheel, m
$Q$	wheel torque, kNm
$W$	wheel load, kN

## 2.2 Wheel numeric

Several authors have presented different kinds of Wheel Numerics, which differ from each others mainly by tyre width and tyre deflection factors. The original dimensionless wheel numerics were

$$\frac{P_R}{W}, \frac{P}{W}, \frac{Q}{W \cdot r_r} = f \left[ \frac{CI \cdot b \cdot d}{W}, S, \frac{b}{d}, \frac{\delta}{h} \right] \quad (2.4)$$

where the wheel and soil variables are the following

$CI$	cone index, soil penetration resistance at a certain depth, kPa
$b$	tyre section width, m
$d$	tyre diameter, m
$W$	tyre load, kN
$S$	slip
$\delta$	tyre deflection, m, generally on hard surface
$h$	tyre section height, m

Semiempirical models presented by different authors are described in Chapter 3, separately for cohesion and friction soils. Terminology is not coherent, but different authors use somewhat different expressions and terms.

Maclaurin (1997) tested a simple wheel numeric, cone index divided by tyre inflation pressure, Eq.(2.5),



$$WN_i = \frac{CI}{p_i} \quad (2.5)$$

but found out, that it was not adequate for describing the tyre/soil interaction. He concludes, that a simple wheel numeric  $C_N$ , Eq.(2.6), proposed by Wismer & Luth (1973) was already better.

$$C_N = \frac{CI \cdot b \cdot d}{W} \quad (2.6)$$

Adding the term  $\sqrt{\frac{\delta}{h}}$ , as proposed by Freitag's (1965) wheel numeric  $N_{CC}$ , Eq (2.5)

$$N_{CC} = \frac{CI \cdot b \cdot d}{W} \cdot \sqrt{\frac{\delta}{h}} \quad (2.5)$$

improved the prediction power. Neither the addition of the tyre shape factor  $\frac{1}{1 + \frac{b}{2 \cdot d}}$  into

the model, as proposed by most WES models,  $N_{CI}$ , Eq.(2.7), improved the model.

$$N_{CI} = \frac{CI \cdot b \cdot d}{W} \cdot \sqrt{\frac{\delta}{h}} \cdot \frac{1}{1 + \frac{b}{2 \cdot d}} \quad (2.7)$$

The Rowland's wheel numeric,  $N_R$ , Eq.(2.2.6), used for determining the MMP, gave similar results.

$$N_R = \frac{CI \cdot b^{0.85} \cdot d^{1.15}}{W} \cdot \left( \frac{\delta}{h} \right)^{0.5} \quad (2.8)$$

Recently Maclaurin (1997) replaced the factor  $\frac{\delta}{h}$  by  $\frac{\delta}{d}$ , which is easier to use without affecting the accuracy of the model. He presented somewhat simpler wheel numeric,  $N_M$ , Eq.(2.2.7) which seemed to give the best estimates.

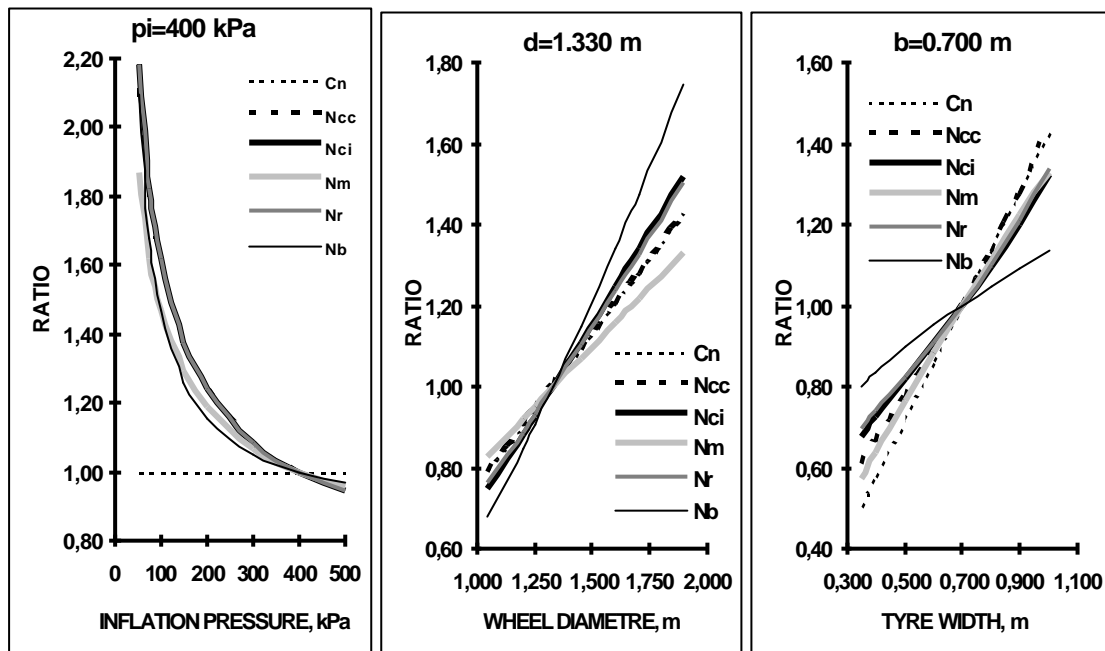
$$N_M = \frac{CI \cdot b^{0.8} \cdot d^{0.8} \cdot \delta^{0.4}}{W} \quad (2.9)$$

Somewhat different type of wheel numeric is presented by Brixius,  $N_B$ , Eq. (2.10)

$$N_B = \frac{CI \cdot b \cdot d}{W} \cdot \left( \frac{1 + 5 \cdot \frac{\delta}{h}}{1 + 3 \cdot \frac{b}{d}} \right) \quad (2.10)$$

As seen, the wheel performance is not linearly dependent on tyre dimensions, but the influence of different factors is more complicated.

For comparison, some wheel numeric are compared in Figure 2.1. Cone index is put to 500 kPa, and tyre inflation pressure, influencing to the tyre deflection, tyre width and wheel diameter are used as an independent variable. The aspect ratio, and thus the section height are intercorrelated with the width. The wheel numeric of the standard tyre ( $W=40$  kN,  $d=1.330$  m,  $b=0.700$  m,  $p_i=400$  kPa) is put to 1, and the relative wheel numeric is depicted in Figure 2.1.



**Figure 2.1.** Relative wheel numeric as a function of changes in some input variables.

Standard value is given in the header. Tyre width and section height are assumed intercorrelated. The tested wheel numerics are

$C_N$ , Eq(2.6), Wismer & Luth (1973)	$N_{CC}$ , Eq(2.5), Freitag (1965)
$N_{CI}$ , Eq(2.2.4), Turnage (1972b)	$N_M$ , Eq(2.9), Maclaurin (1997)
$N_R$ , Eq(2.8), Rowland (1972)	$N_B$ , Eq(2.10), Brixius (1987)

As the Wismer & Luth wheel numeric,  $C_N$ , does not contain deflection as an input variable, it does not fit for comparing tyres with different tyre inflation pressures. There is not large difference between different models, only Maclaurin's wheel numeric ( $N_M$ ) seems to give somewhat lower values for very low inflation pressures, normally out of the practical range of forestry tyres. The Brixius model,  $N_B$ , seems to accentuate the influence of tyre diameter and to omit the influence of tyre width, and the Maclaurin's model,  $N_M$ , reacts just in an inverse way.

### 3. WES-MODELS

#### 3.1 *Models for cohesive soils*

##### 3.1.1 Turnage (1972b), WESFIELD

Turnage's (1972b) models are based on military vehicle field tests in 1960<sup>th</sup>. They were aimed at determining the minimum soil penetration resistance (CI) at a no-go situation. The models may give too low mobility estimates for modern vehicles, as they are based on older technology. The models are reduced to standard 20% slip ( $S = 0.2$ ).

Pull coefficient is

$$\mu_P = 0.8 - \frac{1.31}{N_{CI} - 2.45} \quad (3.1)$$

Towed force coefficient is

$$\mu_R = 0.04 + \frac{0.20}{N_{Ci} - 2.50} \quad (3.2)$$

#### **RCI, remoulded cone index**

Remoulded cone index is soil penetration resistance measured from a specially treated soil sample. It is applicable for cohesion soils after 50 passes.

$$\mu_P = \frac{N_{RCi} - 2.59}{1.25 \cdot N_{RCi} - 1.19} \quad (3.3)$$

$$\mu_P = 0.8 - \frac{1.31}{N_{RCi} - 0.95} \quad (3.4)$$

$$\mu_R = 0.04 + \frac{0.20}{N_{RCi} - 1.35} \quad (3.5)$$

##### 3.1.2 Turnage (1972a), WESLAB

Models are based on the wheel tests on soil bin. Test wheel is fitted with the 1960<sup>th</sup> military (terrain) tyres. Probably the results are assumingly some kind of minimum values because of improvements in tyre technology.

$$\mu_P = 1.51 - \frac{12.37}{N_{Ci} + 5.94} \quad (3.6)$$

$$\mu_R = 0.04 + \frac{0.20}{N_{Ci} - 1.50} \quad (3.7)$$

### 3.1.3 Wismer & Luth (1973)

The classical Wismer & Luth (1973) model marries the WES-model with Janosi-Hanamoto soil reaction model. Wismer & Luth simplified the wheel model by using a standard aspect ratio and tyre deflection, but added the slip into the model. The earlier models were based on standard 20% slip. The model is based on farm tractor traction tests at the end of the 1960<sup>th</sup> and at the beginning of the 1970<sup>th</sup>.

Wismer & Luth used the following standard values for different numerics:

$b/d=0.3$ , compared to an average forwarder tyre  $0.700/1.333=0.525$

$\delta/h=0.2$ , compared to an average forwarder tyre  $0.032/0.385=0.083$

$r/d=0.475$ , which means for a 1.330 m diameter tyre a 0.033 mm deflection, which is about the same as an average forwarder tyre deflection.

The value of term  $(\delta/h)$  differs substantially between the farm and forest tractor tyres.

Thrust coefficient

$$\mu_T = 0.75 \cdot (1 - \exp^{-0.3 C_N \cdot S}) \quad (3.8)$$

Drawbar pull coefficient:

$$\mu_P = 0.75 \cdot (1 - \exp^{-0.3 C_N \cdot S}) - (0.04 + \frac{1.2}{C_N}) \quad (3.9)$$

Rolling resistance coefficient:

$$\mu_R = 0.04 + \frac{1.2}{C_N} \quad (3.10)$$

### 3.1.4 MMP, Rowland (1972) and Rowland & Peel (1975)

Rowland (1972), Rowland and Peel (1975) developed WES modelling, and extended it also for tracked vehicles. He presented the concept of *mean maximum pressure*, MMP, which is the maximum allowable calculated soil contact pressure at no-go situation. The formulae for calculating MMP to different drive systems are discussed in report ETYRE01.

$$\mu_P = 0.12 \cdot N_R^{0.88} \cdot (1 - 0.61 \cdot (1 - S)^4) \quad (3.11)$$

$$\mu_R = 3 \cdot (1 + S) \cdot N_R^{-2,7} \quad (3.12)$$

The Rowland-method, based on determining the MMP, is used in the mobility models of the British Army, and it has been updated several times. The models presented here are based on Melzer's (1984) report. Rowland also presents methods based on a certain wheel numeric,  $N_R$ , Eq.(3.13)

$$N_R = \frac{1,6 \cdot m \cdot CI \cdot b^{0,85} \cdot d^{1,15}}{W_W} \cdot \sqrt{\frac{\delta}{h}} \quad (3.13)$$

$m$       number of tracking wheels on one side, number of axles  
 $W_W$     vehicle weight, kN

Later Larminie (1988) presented the following MMP model. Eq.(3.14) for calculating the rolling resistance coefficient:

$$\mu_R = 0.28 \cdot \left( \frac{MMP}{CI} \right)^{1.95} + HG \quad (3.14)$$

where

$HG$       hard ground resistance coefficient, tyre hysteresis  
             1.3              for car tyres  
             1.7 to 2.8      wheeled armoured cars  
             4.1              tracked armoured fighting vehicles

### 3.1.5 N.I.A.E.-models

N.I.A.E.-models are based on a large number of drawbar pull tests with farm tractors, mainly in the UK. Results are published by different authors in different reports (Gee-Clough (1978), Gee-Clough et al (1978), Dwyer (1984)). There are differences between different tests and models, and one reason is, how the weight transfer to and distribution between the farm tractor axles are taken into account.

$$m_{P20\%} = 0.56 - \frac{0.47}{N_{CI}} \quad (3.15)$$

$$m_R = 0.07 + \frac{0.2}{N_{CI}} \quad (3.16)$$

Later Dwyer (1987) tested broader (up to 0.800 m) low pressure (down to 34 kPa) tyres on farm soils with a low penetration resistance (down to 105 kPa), and developed new models:

$$\mu_P = \left(0,796 - \frac{0,92}{N_{CI}}\right) \cdot \left(1 - \exp^{-1(4,838 + 0,061 \cdot N_{CI})S}\right) \quad (3.17)$$

$$\mu_{P_{MAX}} = 0,796 - \frac{0,92}{N_{CI}} \quad (3.18)$$

$$\mu_{P20\%} = 0,56 - \frac{0,47}{N_{CI}} \quad (3.19)$$

$$\mu_R = 0,049 + \frac{0,287}{N_{CI}} \quad (3.20)$$

### 3.1.6 Brixius (1987)

The Brixius (1987) models are based on the farm tractor draw pull tests carried out by John Deere Co. in USA.

$$\mu_T = 0,88 \cdot (1 - e^{-0,1 \cdot N_B}) \cdot (1 - e^{-7,5S}) + 0,04 \quad (3.21)$$

$$\mu_P = 0,88 \cdot (1 - e^{-0,1 \cdot N_B}) \cdot (1 - e^{-7,5S}) - \left( \frac{1,0}{N_B} + \frac{0,05 \cdot S}{\sqrt{N_B}} \right) \quad (3.22)$$

$$\mu_R = \frac{1,0}{N_B} + 0,04 + \frac{0,05 \cdot S}{\sqrt{N_B}} \quad (3.23)$$

Brixius also developed a new wheel numeric,  $N_B$ , Eq.(3.24)

$$N_B = \frac{CI \cdot b \cdot d}{W} \cdot \left( \frac{1 + 5 \cdot \frac{\delta}{h}}{1 + 3 \cdot \frac{b}{d}} \right) \quad (3.24)$$

### 3.1.7 Ashmore et al (1987).

Ashmore et al. (1987) tested skidder tyres in soil bin under different loading and soil conditions. Soil types were American clays and silts. The test results yielded in models, which differ drastically from the models based on the farm tractor or military vehicle tyre tests. The test tyres were 8 and 10 ply rating skidder tyres, and 103-172 kPa tyre inflation pressures were used. These inflation pressures are remarkably under the forwarder tyre inflation pressures (400 to 450 kPa), used in Finland. Wheel loads varied from 27 to 51 kN, being 55-73% of the rated tyre load. There is no experience on the suitability of these models for estimating the performance of forwarders.

$$\mu_T = 0,47 \cdot (1 - \exp^{-0,20 \cdot N_C \cdot S}) + 0,28 \cdot \left(\frac{W}{W_R}\right) \quad (3.25)$$

$$\mu_P = 0,47 \cdot (1 - \exp^{-0,20 \cdot N_C \cdot S}) + 0,38 \cdot \left(\frac{W}{W_R}\right) - \left(\frac{0,22}{N_C} + 0,20\right) \quad (3.26)$$

$$\mu_R = -0,1 \cdot \left(\frac{W}{W_R}\right) + \frac{0,22}{N_C} + 0,20 \quad (3.27)$$

$W$  actual tyre load, kN

$W_R$  nominal tyre load, rated tyre load, kN

Vechinski et al (1993) studied the performance of different skidder tyres, both new and worn ones, with and without chains on different soils. They concluded, that Ashmore's models give reliable estimates for new tyres on bare homogenous soils, but are not equally good for unhomogeneous soils, or soils surfaced with peat or litter. Soil penetration resistance varied from 297 to 1418 kPa. Their results, "modified Ashmore coefficients" for the following models (Eq. 25 and 26) are given in Table 3.1, for new tyre and Table 3.2 for worn tyre with and without chains.

$$\mu_P = A_1 \cdot (1 - \exp^{-A_2 \cdot N_C \cdot S}) + A_3 \cdot \left(\frac{W}{W_R}\right) - \left(\frac{A_4}{N_C} - A_5\right) \quad (3.28)$$

$$\mu_R = (A_3 - A_6) \cdot \left(\frac{W}{W_R}\right) + \frac{A_4}{N_C} + A_5 \quad (3.29)$$

**Table 3.1.** Coefficients for models (3.28)-(3.29) for new skidder tyres.

Coefficient	Original	Modified				
	Ashmore	Decatur claysilt	Norfolk Sandysilt	Oktibeeha clay	Sharkey claysilt	All
$A_1$	<b>0.47</b>	0.52	0.48	0.58	0.42	0.50
$A_2$	<b>0.20</b>	0.22	0.21	0.17	0.21	15.15
$A_3$	<b>0.38</b>	0.42	0.38	0.36	0.35	0.42
$A_4$	<b>0.22</b>	0.22	0.21	0.19	0.19	-4.89
$A_5$	<b>0.20</b>	0.19	0.21	0.20	0.19	-1.31
$A_6$	<b>0.48</b>	0.44	0.50	0.56	0.53	0.82
Soil properties						
Surface		no	No	litter	peat	
Sand, %		27	<b>72</b>	21	2	
Silt, %		<b>43</b>	17	18	41	
Clay, %		30	11	<b>61</b>	<b>57</b>	
Moisture, %		15.5	17.7	25.2	28.3	
Density, kg/m <sup>3</sup>		1080	1420	1230	1130	

**Table 3.2.** Coefficients for models (3.28)-(3.29) for worn out skidder tyres.

Coefficient	Original	Modified							
		Decatur		Norfolk		Oktibeeha		Sharkey	
		Worn	Chain	Worn	Chain	Worn	Chain	Worn	Chain
A <sub>1</sub>	<b>0.47</b>	0.52	0.52	0.45	0.48	0.45	0.54	0.54	0.77
A <sub>2</sub>	<b>0.20</b>	0.22	0.22	0.22	0.20	0.19	0.18	1.25	1.94
A <sub>3</sub>	<b>0.38</b>	0.41	0.42	0.39	0.39	0.38	0.38	0.35	0.28
A <sub>4</sub>	<b>0.22</b>	0.21	0.21	0.23	0.22	0.22	0.19	-0.07	-0.24
A <sub>5</sub>	<b>0.20</b>	0.20	0.21	0.20	0.19	0.22	0.22	0.37	-0.18
A <sub>6</sub>	<b>0.48</b>	0.44	0.43	0.48	0.46	0.50	0.53	0.73	0.72

Rummer & Ashmore (1985) developed the rolling resistance coefficient model for skidders operating on firm soils.

$$\mu_R = 0.24 \cdot \left( \frac{W_W}{CI \cdot b \cdot d} \right) + 0.06 \cdot \left( \frac{W_W}{4 \cdot W_R} \right) \quad (3.30)$$

The model can be modified for one wheel, with a certain accuracy, to be as follows:

$$\mu_R = \frac{1.15}{C_n} + 0.06 \cdot \left( \frac{W}{W_R} \right) \quad (3.31)$$

W<sub>R</sub> rated load of tire as defined by the Tire and Rim Association Yearbook  
W<sub>W</sub> vehicle total weight, kN  
W wheel load, Kn

### 3.1.8 Maclaurin (1990).

Maclaurin (1990) studied in the UK the performance of military vehicle terrain tyres using a single wheel tester. The results can be applied for military terrain tyres. He found out, that the soil surface properties influence on the tyre performance: on poor bearing surface the tread pattern and the tyre inflation pressure influenced on mobility, but on harder surface tyre tread pattern had less significant effect (Maclaurin 1981),.

$$\mu_P = 0.8 - \frac{3.2}{N_{Ci} + 1.91} \quad (3.32)$$

$$\mu_R = 0.017 + \frac{0.453}{N_{Ci}} \quad (3.33)$$



Later Maclaurin (1997) analysed the bias of the different factors on wheel numeric and concluded, that “rounded wheel numeric”,  $N_M$  gave less biased estimates than the use of  $N_{CI}$ .

$$N_M = \frac{CI \cdot b^{0.8} \cdot d^{0.8} \cdot \delta^{0.4}}{W} \quad (3.34)$$

### 3.1.9 Sharma & Pandey (1998)

Sharma & Pandey (1998) studied farm tractor tyres in soil bin using Indian sandy clay loam soils and later (Sharma & Pandey 2001) carried out a large number of field tests with agricultural tractors in Indian farming conditions in order to determine the optimum tyre configuration for small 2-wheel drive farm tractors. They proposed a definition for pull at 0-condition, which is close to net traction but a little bit higher apparent slip, 30%. The models do not seem, however, to apply well to forestry tyres, but may be used for narrower tractor tyres ( $b=0.280$  to  $0.350$  m,  $b/d=0.23$  to  $0.25$ ) with large deflection ( $\delta/h=0.18$  to  $0.26$ ).

$$N_{CC} = \frac{CI \cdot b \cdot d}{W} \cdot \sqrt{\frac{\delta}{h}} \quad (3.35)$$

$$\mu_{P_0} = 0.76 \cdot \left(1 - e^{-0.07 \cdot N_{CC} \cdot S}\right) \quad (3.36)$$

$$\mu_{T_0} = 0.36 \cdot \left(1 - e^{-0.35 \cdot N_{CC} \cdot S}\right) \quad (3.37)$$

where

$\mu_{P_0}$	pull coefficient
$\mu_{T_0}$	thrust coefficient
$N_{CC}$	Freitag Wheel numeric
$S$	slip, decimal

### 3.1.10 McAllister (1983)

McAllister (1983) studied the rolling resistance of farm tractor tyres

**For cross ply**

$$\mu_R = 0.054 + \frac{0.323}{N_{CI}} \quad (3.38)$$

**For belt tyres**

$$\mu_R = 0.037 + \frac{0.321}{N_{CI}} \quad (3.39)$$

### 3.2 Models for friction soils

Because the soil reaction of friction soils depends also from the loading state, soil penetration resistance alone is a less suitable variable for friction soil models. Therefore more sophisticated models, including the soil density were developed, but often they also demand laboratory tests for determining some coefficients. Therefore only some simple approaches are presented here.

#### 3.2.1 Turnage 1972

The Turnage's models (Turnage 1972a, Turnage 1984) for sandy soils are based on Sand Numeric,  $N_s$ .

$$\mu_{\text{TNET}} = 0.5 - \frac{5.9}{N_s + 7} \quad (3.40)$$

$$\mu_{\text{T20\%}} = 0.53 - \frac{4.5}{N_s + 3.7} \quad (3.41)$$

His soil bin test models (Turnage 1972b) are as follows

$$\mu_{\text{TNET}} = \frac{N_s - 5.50}{1.92 \cdot N_s + 37.20} \quad (3.42)$$

$$\mu_{\text{T20\%}} = 0.521 - \frac{12.97}{N_s + 19.4} \quad (3.43)$$

$$\mu_{\text{RR}} = \frac{0.0385 \cdot N_s + 0.481}{N_s - 2.58} + 0.025 \quad (3.44)$$

The sand wheel numeric,  $N_s$ , is given in Eq(3.2.1.6).

$$N_s = \frac{G_{\text{CI}} \cdot (b \cdot d)^{\frac{3}{2}}}{W} \cdot \frac{\delta}{h} \quad (3.45)$$

where

$G_{\text{CI}}$	soil penetration gradient
$b$	tyre width, m
$d$	tyre diameter, m
$W$	tyre load, kN
$\delta$	tyre deflection, m
$h$	tyre section height, m

### 3.2.2 Paul (1984)

Paul (1984) studied the performance of military trucks on Indian sand dunes using Turnage's (1984) models, and found, that the models gave underestimates, but are still rather reliable.

$$\mu_{RR} = 0.025 + \frac{0.0385 \cdot N_s + 0.481}{N_s - 2.58} \quad (3.46)$$

$$\mu_{T20\%} = \frac{0.521 \cdot N_s - 2.86}{N_s + 19.4} \quad (3.47)$$

### 3.2.3 Li et al. (1990)

Li et al. (1990) studied 4WD trucks on delta sand soil in China and developed passing probability theory calculations for varying soil conditions.

$$\mu_{TNET} = 0.458 - 0.447 \cdot \exp^{-0.3N_\alpha \cdot S} + 0.157 \cdot N_\alpha - 0.514 \cdot S \quad (3.48)$$

**note:** the third term may be also  $0.0157 \cdot N_\alpha$

$$\mu_R = 0.44 - 0.01 \cdot N_\beta + \sqrt{(0.44 - 0.01 \cdot N_\beta)^2 + 0.0002 \cdot N_\beta + 0.08} \quad (3.49)$$

$$N_\alpha = \frac{G \cdot (b \cdot d)}{W} \cdot \frac{\delta}{h} \quad (3.50)$$

$$N_\beta = \frac{G \cdot (b \cdot d)^{\frac{3}{2}}}{W \cdot \left(1 - \frac{\delta}{h}\right)^3 \cdot \left(1 + \frac{b}{d}\right)} \quad (3.51)$$

## 3.3 Multipass models

Most of the WES models are based on an analysis of a single wheel or axle, either using a single wheel tester of a farm tractor. Some of the results are based on the field tests of a certain vehicle, usually with equally sized and loaded wheels, and then calculated for a single wheel. Real multipass models are scarce.

### 3.3.1 Dwyer et al (1977)

Dwyer et al. (1977) studied the rolling resistance and drawbar pull of a wheel during the second pass on the same track and developed the following models:

$$\frac{\mu_{R1}}{\mu_{R2}} = 1 - \frac{0.896}{N_{CI}} \quad (3.52)$$

$$\frac{\mu_{T1}}{\mu_{T2}} = 1 + \frac{0.620}{N_{CI}} \quad (3.53)$$

## 4. SINKAGE AND RUT DEPTH MODELS

Even transport/environment-interface has had a certain interest in terramechanics, for long the mobility studies have been numerous in comparison with modelling the soil/tyre sinkage or rut depth. Only a few authors have presented sinkage models based on WES-method. The earliest is Rowland's model from the beginning of early 70<sup>th</sup>. Maclaurin presented his model at the beginning of -90<sup>th</sup>.

Sinkage and rut models are generally for one pass of a certain wheel or for a certain fixed number of passes. In fact, it is important to define also the concept of "multipass". For a single wheel tester, the multipass is the sinkage or the rut depth observed after a certain number of passes of a single wheel over the same test track. For tractor tests the concept is generally different, the sinkage or rut depth is measured after a certain number of tractor passes over a certain test lane, and, for example, the number of single wheels depends on the tractor configuration. The problem becomes even more complicated when a forwarder transport is to be modelled. The empty tractor travels over a certain point and returns loaded. In this case the wheel load between loadings differs radically. It is therefore evident, that simple rut depth models, based on forwarder pass concept may differ from models based on a wheel, or a vehicle with constant, equal loads. For example, a farm tractor can easier be fitted to single wheel tester models than a 6- or 8- wheeled forwarder. Therefore, for forwarder and skidder studies, more emphasise must be put on the test configuration and data analysis, if more reliable models will be developed. The following cases can be discerned

- single wheel tester, **single and multipass wheel model**
- forest tractor
  - (rather) similar wheel load and size in front and rear wheels
    - constant wheel loads (circular test tracks, harvesters), **multipass wheel model, single and multipass tractor model**
    - different wheel loads (return empty, transport loaded, generally two-way traffic with skidders and forwarders), **single and multi cyclepass tractor model** (even may be based on a single wheel parameters)
  - different tyre sizes and wheel loads in front and rear axles
    - constant wheel loads (circular test tracks, harvesters) **single and multipass tractor model** (even may be based on a single wheel parameters)
    - different wheel loads (return empty, transport loaded, generally two-way traffic with skidders and forwarders), **single and multi cyclepass tractor model** (even may be based on a single wheel parameters)

For skidder and forwarder operations cyclepass concept is necessary, because the loading sequence differs from other cases. **Multipass** concept is based on the same tractor configuration on one way traffic, **multicycle** concept on the cycles of two way traffic of a certain tractor travelling empty to and loaded fro.

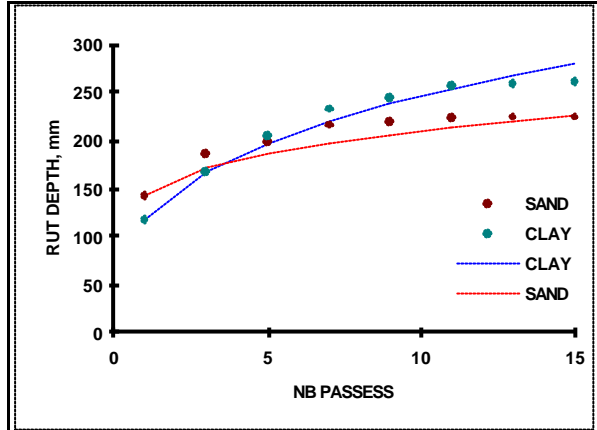


Figure 4.1. Rut depth as function of number of passes on friction and cohesive soil. (Meek 1996)

After different studies it can be concluded, that the soil reaction mechanism and rut formation process on friction and cohesive soils are different. As a rule, on friction soils the soil is compacted, and the rut depth is asymptotic to a certain maximum rut depth. In cohesive soils the soil strength consists, partly or totally, of the cohesive component, and the cohesive bindings between soils particles break under repetitive and/or excessive loads. Therefore the rut formation increases rather linearly as a function of number of passes, as seen from Figure 4.1.

#### 4.1 Sinkage models

In some cases the sinkage is measured as the wheel radius minus distance of the axle center to the soil surface. Maclaurin (1990) defines sinkage as ‘*rut depth to pre-run surface*’, which is in practice the same as rut depth measured from the surrounding level.

##### 4.1.1 Rowland’s sinkage model (1972)

In fact, the Rowland’s (1972) model is not a typical WES-model, but belongs to the development phase modelling, when soil engineering theories were introduced in the mobility and trafficability modelling.

$$z = \frac{\text{MMP}}{\gamma \cdot N} - 0.5 \cdot b \quad (4.1)$$

where

- z is sinkage, m
- b tyre width, m
- MMP mean maximum pressure
- $\gamma$  soil density, N/m<sup>3</sup>
- N Terzaghi constant, Figure 4.2

#### 4.1.2 Maclaurin (1990)

Maclaurin (1990) observed the sinkage when testing military tyres using the 5th wheel tester on terrain conditions and developed the following wheel sinkage model:

$$z = d \cdot \left( \frac{0.224}{N_{CI}^{1.25}} \right) \quad (4.2)$$

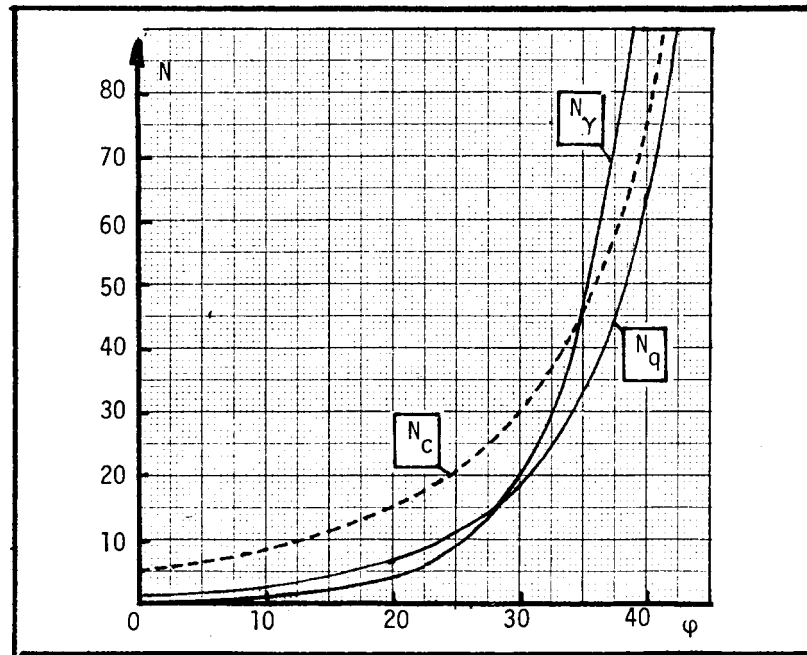


Figure 4.2. Terzaghi constants (Rantamäki et al 1979)

#### 4.1.3 Gee-Glough (1985)

Gee-Glough (1985) developed rolling resistance model for rigid tyre as a function of sinkage. Based to his model, the following sinkage model can be developed, Eq. (4.1.3).

$$z = \frac{\mu_R \cdot d}{\left( 0.63 + 0.34 \cdot \frac{b}{d} \right)^2} \quad (4.3)$$

For the rolling resistance coefficient the modified N.I.A.E-model, Eq(4.1.4) can be used. The model is the same as Eq(3.1.5.6) without the tyre deformation resistance.

$$\mu_R = \frac{0.287}{N_{CI}} \quad (4.4)$$

## 4.2 Rut depth models

Rut depth models differ from sinkage models in the respect of observing the wheel. When measuring the sinkage the wheel is loading the soil, in measuring the rut the wheel has already passed the observation point. Different rut depth models, based on soil penetration resistance measurements have been developed recently, when the environmental effects of transportation have become more decisive.

### 4.2.1 Anttila (1998)

Anttila (1998) used WES-method as frame of reference and developed rut depth models for different wheel numerics and  $z$  and  $z/d$ - variations. His main cyclepass models are the following:

$$z_R = a + \frac{b}{N} \quad (4.5)$$

where

- $z_N$  is rut depth, m
- $a, b$  empirical constants
- $N$  one of the wheel numerics

The constants are in Table 4.1.

**Table 4.1.** Constants for the Anttila's rut depth models 4.2.1.

	A	b	N
Model 1	0.003	0.380	$N_{CC}$
Model 2	0.000	0.328	$N_{ci}$
Model 3	0.005	1.212	$C_N$

The other types of models uses dimensionless  $z/d$ -variable

$$z_R = \left( a + \frac{b}{N} \right) \cdot d \quad (4.6)$$

The constant for the model 4.2.2 are in Table 4.2.

**Table 4.2.** Constants for the Anttila's rut depth models 4.2.2.

	A	b	N
Model 4	0.001	0.287	$N_{CC}$
Model 5	-0.001	0.248	$N_{ci}$

Model 6	0.003	0.910	$C_N$
---------	-------	-------	-------

#### 4.2.2 Saarilahti et. al (1997)

Rummukainen & Ala-Ilomäki (1986) studied rut formation in connection with harvesting on peatlands. Later the data was used for developing rut depth models using WES-variables (Saarilahti et al. 1997). The model is based on specially fitted forest tractors with tracks on tandem axles, even the wheel numerics are calculated for simple wheel. Therefore the model may give some underestimates for normal tractors on peatland. Model is tractor multipass model, because tests were carried out with loaded tractors on one way test lane.

$$z_{RUT} = \frac{0.142}{N_{CI}^{0.83}} \cdot d \quad (4.7)$$

Later new models were developed based on the same original data, but using somewhat more exact estimates on tyre deflection, which was not observed during the field tests. Also a new wheel numeric, proposed by Maclaurin (1997) was included, Figure 4.3. The Maclaurin's wheel numeric seemed to give the highest correlation coefficients, but there is no practical difference between the three developed models, Eq.(4.2.3) to Eq(4.2.6).

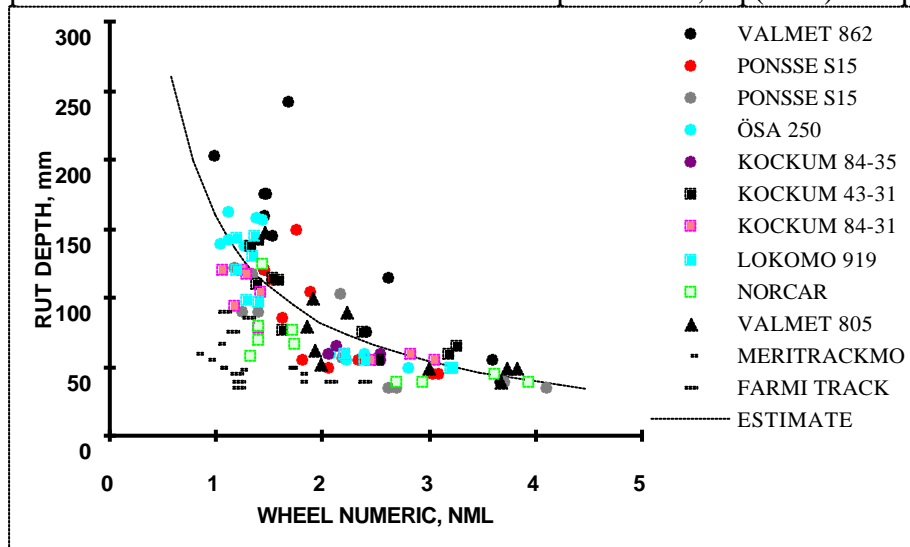


Figure 4.3. Rut depth as a function of Maclaurin's wheel numeric

$$z_{RUT} = \frac{0.130}{N_{ML}^{0.88}} \cdot d \quad r^2=0.666 \quad (4.8)$$



$$z_{\text{RUT}} = \frac{0.432}{C_N^{0.79}} \cdot d \quad r^2=0.507 \quad (4.9)$$

$$z_{\text{RUT}} = \frac{0.108}{N_{\text{CI}}^{0.76}} \cdot d \quad r^2=0.653 \quad (4.10)$$

#### 4.2.3 Ala-Ilomäki & Saarilahti (1990)

Ala-Ilomäki & Saarilahti (1990) studied the rut depth of a garden tractor tyre on peat soil using a forced slip tester. They concluded, that the slip plays an important role in rut formation. Their model, Eq. (4.2.7.) may give too low values for forest tractor with if small slip values are used, but may suit better for conditions, where using of higher slip is needed. Many of the models do not use slip as an input variable. The validity of the model must be studied more in detail, however. The model is based on rut depth after 5<sup>th</sup> pass, which means, that they are valid about for a single pass of a forest tractor.

$$z_{\text{RUT}} = 0.122 \cdot \frac{\text{NGP} \cdot S^{1.41}}{\text{CI}^{0.54}} \quad (4.11)$$

where

$z_{\text{RUT}}$	rut depth, m
NGP	nominal ground pressure, kPa
S	slip, %
CI	cone index, kPa

#### 4.2.4 Rantala (2001)

Rantala (2001) compared three different methods to predict the rut formation

- the soil bearing capacity modulus (E-modulus), measured by a portable device, Loadman
- WES-method, based on penetrometer
- soil critical moisture method (ForstBefahrung), using TDR soil moisture measuring device and concluded that the measured rut depth in practice may be remarkably deeper than predicted using different method, because of remarkable variation in actual load distribution, and dynamic loads, compared to static wheel load, generally observed during field observations.

The analyse of the data permitted to develop the following models, Eq(4.12-4.20).

**All soils** combined (all data)

$$z = 0.010 + \frac{0.610}{N_{\text{CI}}} \quad (r^2=0.389) \quad (4.12)$$

$$z = \frac{0.875}{N_{CI}^{1.36}} \quad (r^2=0.286) \quad (4.13)$$

**Peat and clay (soft soils)**

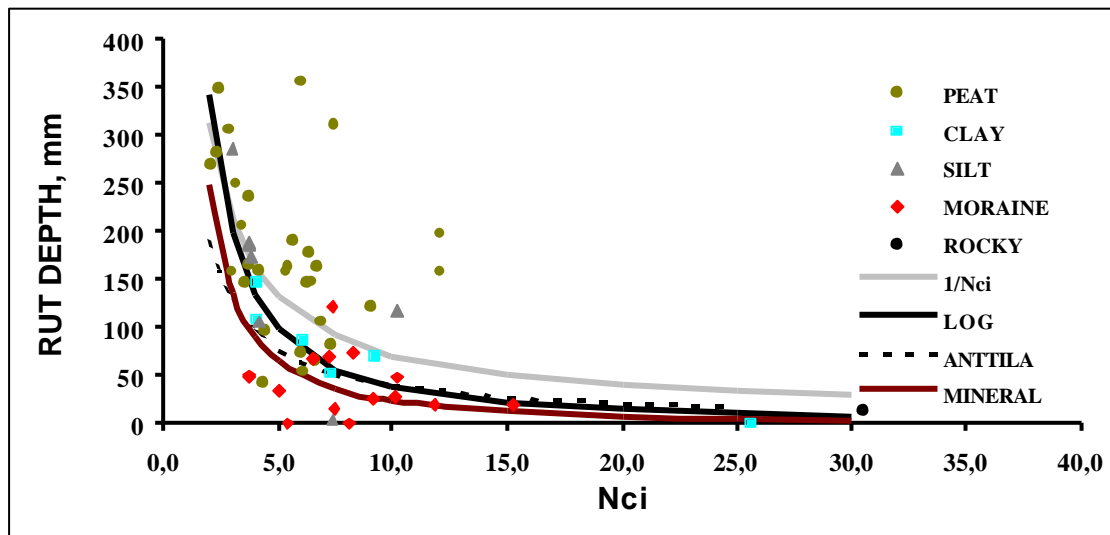
$$z = 0.059 + \frac{0.490}{N_{CI}} \quad (r^2=0.315) \quad (4.14)$$

$$z = \frac{0.989}{N_{CI}^{1.23}} \quad (r^2=0.396) \quad (4.15)$$

**Mineral soils**

$$z = -0.026 + \frac{0.629}{N_{CI}} \quad (r^2=0.493) \quad (4.16)$$

$$z = \frac{0.678}{N_{CI}^{1.46}} \quad (r^2=0.273) \quad (4.17)$$



**Figure 4.4 Different Rantala (2001) models compared to Anttila (1979) model.**  
Adding the volumetric moisture content added slightly the prediction power, Eq.(4.20)

$$z = -0.042 + 0.0055 \cdot MC_{VOL} + \frac{875}{N_{CI}^{1.36}} \quad (r^2=0.513) \quad (4.20)$$

where

$z$  is first cycle rut depth, m  
 $N_{CI}$  wheel numeric  
 $MC_{VOL}$  volumetric moisture content, %

### 4.3 *Multipass rut dept*

When planning of transportation systems also the number of loads a certain soil can bear is important to know. Therefore developing of multipass transport models, in stead of single wheel rut models is of first importance.

#### 4.3.1 Soil reactions under repetitive loading

Scholander (1974) used terramechanical frame of reference for his studies on forest tractor mobility, and carried out repetitive plate loading tests on different Swedish forest soil types. He found out, that the general equation for the settlement during load test is as follows:

$$s_n = s_1 \cdot n^{\frac{1}{a}} \quad (4.12)$$

where

$s_n$  settlement after the  $n$  loading cycle, m  
 $s_1$  settlement after the 1<sup>st</sup> cycle, m  
 $n$  number of cycles  
 $a$  repeatedness coefficient, depending on soil properties and load

The coefficient  $a$ , called repeatedness coefficient by Scholander, is rather similar to multipass coefficient introduced by some other authors, and therefore the term multipass coefficient is used generally in this report for the coefficient, with which the development of rut depth a function of number of loadings can be described with a certain degree. The average values for the multipass coefficient  $a$  are as given in Table 4.3. It can be seen, that the multipass coefficient is low, 2-5 for wet and fine grained soils, and grows higher for dryer and coarser soils. This means, that on wet fine grained soils (low bearing soils) each successive load causes deeper additional increase in rut depth than on drier coarser (good bearing capacity) soils.

Table 4.3. Multipass coefficient  $a$  for different soil types under different moisture conditions after Scholander (1974)

Soil type				Multipass coefficient
Silt	Fine sand	Sand	Gravel	
Particle size, mm				
0.002-0.02	0.02-0.2	0.2-2	2-20	
Soil moisture, %				
20-35				2
20-30				5
	20-30	10-25		7
10-20	10-30	5-20		10
		10-20		13
		5-20	5-15	17
			5-10	26

#### 4.3.2 Tractor multipass

After Abebe (1989) the general model for of multipass sinkage is:

$$z_N = z_1 \cdot n^{\frac{1}{a}} \quad (4.13)$$

where

- $z_N$  sinkage after pass  $N$ , m
- $z_1$  first pass sinkage, m
- $n$  number of passes
- $a$  multipass coefficient from Table 4.4.

This is, in fact, similar to the Scholander's settlement model, Eq.(4.3.1).

Table 4.4. Multipass coefficient  $a$  for multipass Equation(4.3.1) (After Abebe 1989)

Soil and load conditions	Multipass coefficient $a$
Loose soil, low load	2 to 3
Medium bearing soil, medium load	3 to 4
Bearing soil, heavy load	4 to 5

Results of Equation (4.3.2) are compared with Meek's observations in Figure 4.3. It seems that coefficient  $a=6$  for sand and  $a=3$  for clay give the best match with Meek's data.

### 4.3.3 Modelling of the multipass coefficient

If the form of a multipass function is expected to follow the Abebe's model, Eq.(4.3.2), we can write the following equations

$$z_i = z_1 \cdot i^m \quad (4.14a)$$

$$z_j = z_1 \cdot j^m \quad (4.14b)$$

where

$i, j$       ordinary number of passes  
 $z_n$       rut depth, m  
 $m$       inverse of multipass coefficient,  $m = \frac{1}{a}$

The pair of equations can be solved, and the coefficient  $m$  calculated from empirical data matrix

$$m = \frac{\ln(z_j) - \ln(z_i)}{\ln(j) - \ln(i)} \quad (4.15)$$

and the multipass coefficient  $a$  is

$$a = \frac{\ln(j) - \ln(i)}{\ln(z_j) - \ln(z_i)} \quad (4.16)$$

Based on field tests on soft soils Freitag (1965) concluded the following model

$$z = \left( z_1^2 + z_2^2 \right)^{0.5} \quad (4.17)$$

where

$z$       rut depth after 2<sup>nd</sup> pass, m  
 $z_1$       rut depth after 1<sup>st</sup> pass, m  
 $z_2$       estimated rut depth after 2<sup>nd</sup> pass without no prior soil disturbance, m

For the equal tyres it leads the multipass coefficient of 2, e.g.

$$z_n = z_1 \cdot n^{\frac{1}{2}} \quad (4.18)$$

#### 4.4 Multipass rut depth models

##### 4.4.1 Turnage's multipass for equal wheels

Turnage (1972c) studied rut depth on prepared, uniform, weak soils and presented the following model. Evidently it reflects the same test conditions as old WES-mobility models, giving extreme values on weaker soils.

$$z = d \cdot 4.61 \cdot n^{0.5} \cdot \left( \frac{q}{NGP} \right)^{-2.6} \quad (4.19)$$

where

d	tyre diameter, m
z	rut depth, m
n	number of passes
q	penetration resistance, kPa
NGP	nominal ground pressure, kPa

The multipass coefficient is constant,  $a=2$

##### 4.4.2 Multipass coefficient based on Dwyer et al (1977) model

Using Dwyer et al.'s (1977) second pass rolling resistance model, Eq. (3.52) and basing on the assumption, that the rut depth is rolling resistance coefficient to a certain power,  $\alpha$ , and letting it into Eq. (4.16) the following multipass coefficient model can be constructed, Eq.(4.20):

$$a = \frac{\ln(2)}{\ln \left( z_1 \cdot \left( \frac{N_{CI}}{N_{CI} - 0.896} \right)^\alpha \right) - \ln(z_1)} \quad (4.20)$$

where

a	multipass coefficient
$z_1$	rut depth after 1st pass, m
$\alpha$	rolling resistance to rut depth conversion coefficient use $\alpha=1.25$ (Maclaurin's data)
$N_{CI}$	wheel numeric

##### 4.4.3 Wronsky & Humphreys' tractor multipass method

Wronski & Humphreys (1994) based their Effective Ground Pressure (EGP) models on the old WES-studies, combining the Turnage's (1972b) and Freitag's (1965) multipass models. They introduced Effective Ground Pressure (EGP) concept.

For wheeled 2-axle tractor

$$EGP_{\text{wheel}} = 0.88 \cdot \left( \frac{d_2}{d_s} \right)^{0.384} \cdot NGP_2 \cdot \left( 1 + \left( \left( \frac{d_1}{d_2} \right)^2 \cdot \left( \frac{NGP_1}{NGP_2} \right)^{5.2} \right) \right)^{0.192} \quad (4.21)$$

where

$EGP_{\text{wheel}}$  effective ground pressure for a wheeled vehicle, kPa

$d_i$  wheel<sub>i</sub> diameter, m

$d_s$  diameter of a reference wheel,  $d_s=1.500$  m

$NGP_i$  nominal ground pressure of wheel<sub>i</sub>, kPa

For machines with 3 or 4 axles, at first the EGP of the first virtual axle (1 and 2) is calculated, and the value is used for the third axle, etc.

For a tracked machine the EGP is

$$EGP_{\text{tracks}} = 0.8 \cdot NGP \cdot \left( \frac{MMP}{2 \cdot NGP} \right)^{1.23} \quad (4.22)$$

where

$EGP_{\text{tracks}}$  effective ground pressure for a tracked vehicle, kPa

$NGP$  nominal ground pressure, kPa

$MMP$  mean maximum ground pressure

$$MMP = \frac{1.26 \cdot W_w}{2 \cdot m \cdot b \cdot \sqrt{p \cdot d}} \quad (4.23)$$

where

$MMP$  mean maximum ground pressure, kPa

$W_w$  vehicle weight, kN

$m$  number of axles

$b$  track width, m

$p$  track plate pitch, m

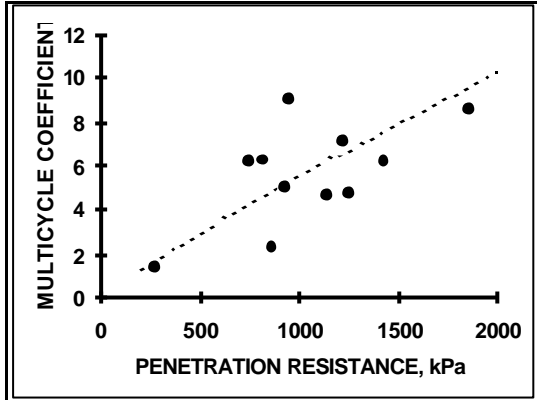
$d$  road wheel diameter, m

#### 4.5 Multicycle coefficient

Multicycle coefficient can be assessed from tractor transport studies.

##### 4.5.1 Anttila's (1998) data

Anttila (1998) measured the rut depth after 1...5 forwarder cycles. The load size was not always the same, but varied within “normal” full load limits. The following models Eq(4.5.1.) and Eq(4.5.2) can be derived from his original data.



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Figure 4.5. Multicycle coefficient as a function of penetration resistance

Eq.(4.25) are presented in Figure 4.4.

Multicycle coefficient based on wheel numeric,  $N_{CI}$ :

$$a = 1.5 \cdot N_{CI}^{0.7} \quad (4.24)$$

Multicycle coefficient based on cone penetration resistance,  $q$ :

$$a = 0.011 \cdot q^{0.9} \quad (4.25)$$

The data and the estimates of model

#### 4.5.2 Rummukainen & Ala-Ilomäki (1988) data

Multipass coefficient seemed rather independent on wheel numeric, which uses deflection as one of the input variables,  $N_{CI}$  and  $N_{ML}$ , see Figure 4.5.

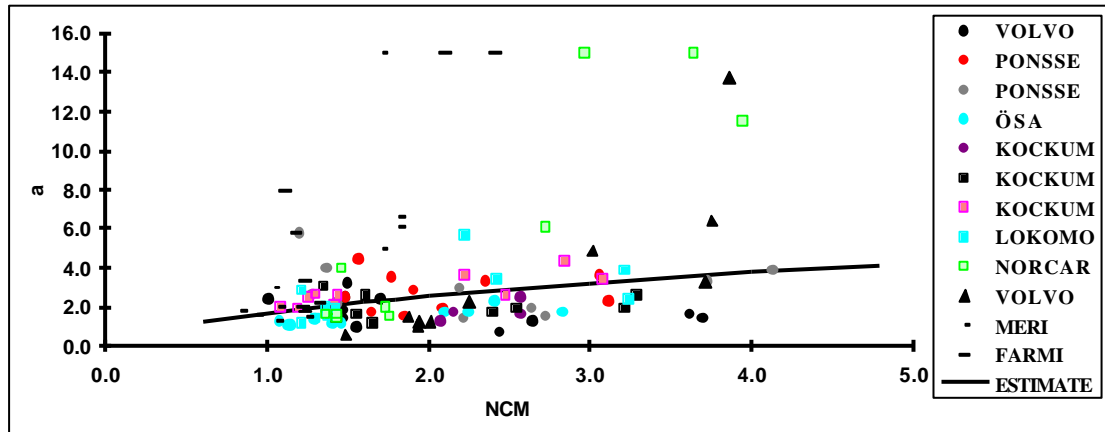


Figure 4.6. Multicycle coefficient as function of Maclaurin's wheel numeric fitted with Rummukainen and Ala-Ilomäki (1988) data.

The developed multipass coefficient models are

$$a = 2.0 \cdot N_{CI}^{0.33} \quad r^2=0.047 \quad (4.26)$$

$$a = 1.7 \cdot N_{ML}^{0.57} \quad r^2=0.105 \quad (4.27)$$



Due to the low correlation coefficient and the gradual slope factor when using above mentioned wheel numerics, the constant multicycle coefficient,  $a=2$ , can be used. In fact, it is the same as proposed by Turnage, see Chapter 4.4.1.

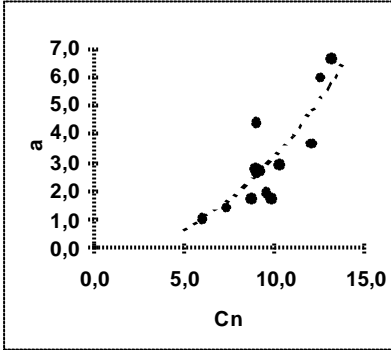


Figure 4.7. Correlation between multicycle coefficient and wheel numeric  $C_N$  in average tractor data

However, the multicycle coefficient,  $a$ , seemed too be correlated with the simple wheel numeric,  $C_N$ . There were very strong correlation between the multicycle coefficient and wheel numeric in the average tractor data, see Figure 2.6.

$$a = 0.02 \cdot C_N^{2.2} \quad r^2=0.623 \quad (4.28)$$

This is due to the fact, that for the higher  $C_N$  values the contact pressure started to be lower than the bearing capacity of the substrate, and the deepening of the rut depth after the tractor pass became less important. This model (TRACTORS in Figure 4.7) cannot, however, be used to estimate the multipass coefficient, (DATA in Figure 4.7), but the model developed from the data must be used, Eq.(4.29):

$$a = 0.3 \cdot C_N \quad r^2=0.298 \quad (4.29)$$

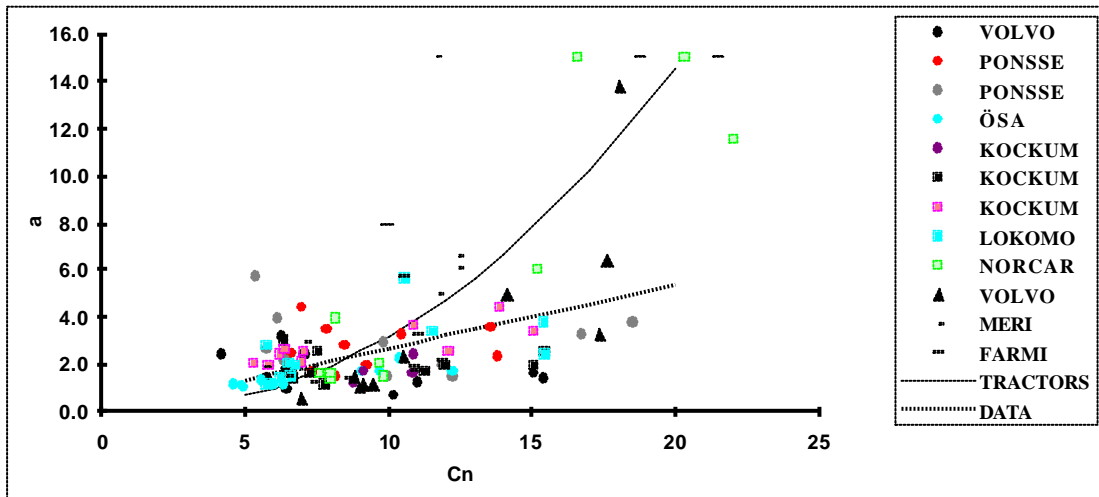


Figure 4.8. Multicycle coefficient as function of the wheel numeric  $C_N$

Rear wheel load or cone index did not correlate significantly with multicycle coefficient.

The fixed multicycle coefficient,  $a=2$ , and models Eq(4.27) and (4.29) are compared against the Rummukainen et Ala-Ilomäki (1988) data in Figure 4.8. There is no large difference

between the different estimates. The variation in multicycle coefficient based on  $C_N$  is the highest, and therefore it gives also the highest estimates for the most sensitive sites. For practical applications, each model is reliable enough to screen out the sensitive site/vehicle combinations.

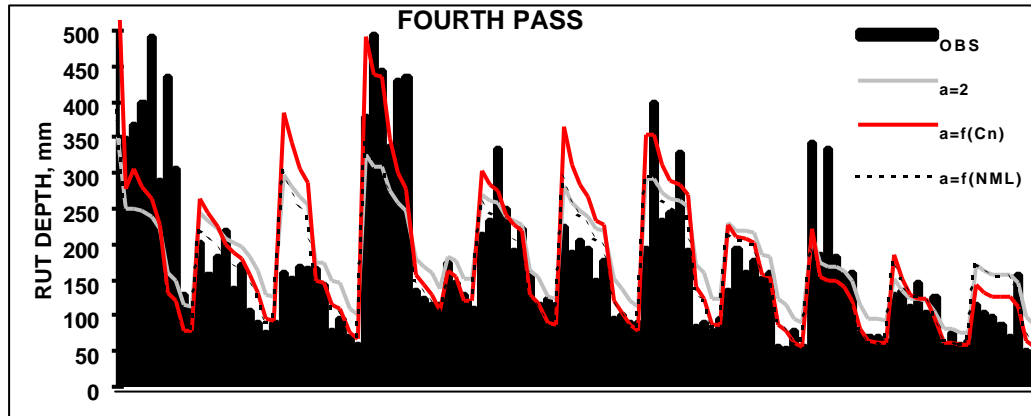


Figure 4.9 Comparison of the estimated rut depth after the fourth pass using different multicycle coefficients

#### 4.5.3 Larminie's (1988) multipass coefficient

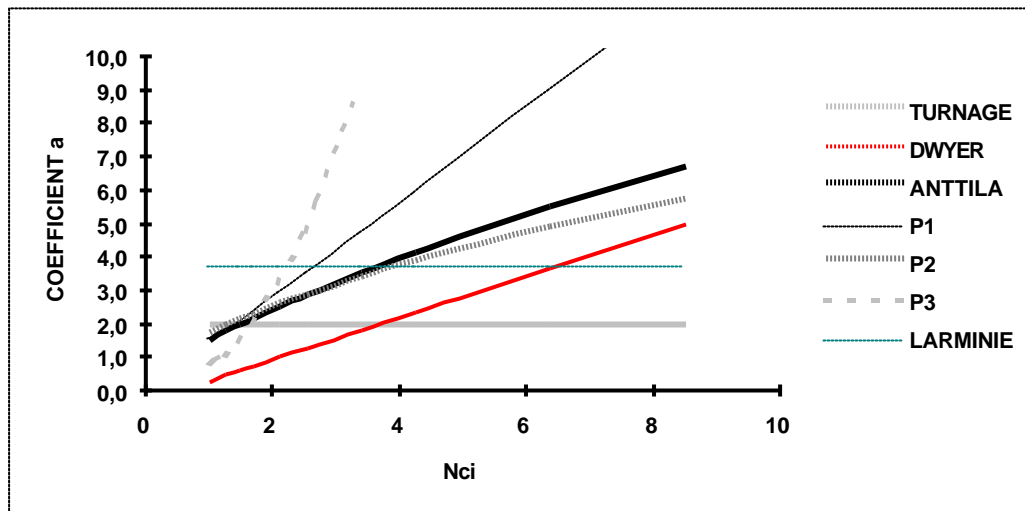
Larminie (1988) gives the following Table, Table 4.5, for estimating the multiple pass rating cone index multiplier, based on one pass (go/no go) RCI. The one-pass multiplier corresponds to the multipass coefficient  $a=3.8$

Table 4.5. Multipass multiplier for fine grained soils (Larminie 1988)

Number of passes	1	2	5	10	25	50
One-pass multiplier	1	1.2	1.63	1.85	2.35	2.8

#### 4.5.4 Comparison of the multipass coefficients

The multipass coefficients proposed by different authors differs somewhat, some authors uses a fixed coefficient, but evidently multipass coefficient is also dependent on wheel/soil characteristics. Therefore it seems reasonable to use some multipass model, which uses wheel numeric as an input variable. The different models are compared in Figure 4.9.



**Figure 4.10. Different multipass coefficients as a function of wheel numeric  $N_{CI}$**

#### 4.6 Testing of the multipass models

Maclaurin's wheel sinkage model and Anttila's tractor rut depth model are compared in Figure 4.9. The calculation is based on two average forwarders, one 6-wheeled and the other 8-wheeled, on three soils ( $CI = 450, 550$  and  $750$  kPa), using Anttila's multipass coefficient. Used wheel characteristics are given in Table 4.6.

**Table 4.6. Wheel characteristics used in model comparison**

Wheel Characteristics	6-wheeled			8-wheeled		
	Front	Rear		Front	Rear	
		Empty	Loaded		Empty	Loaded
d, m	1,634	1,333	1,333	1,333	1,333	1,333
b, m	0,700	0,600	0,600	0,700	0,700	0,700
$\delta$ , m	0,023	0,008	0,023	0,012	0,008	0,023
h, m	0,385	0,390	0,385	0,385	0,385	0,385
W, kN	30	10	30	15	10	30

A certain fit with the two approaches can be seen, which shows, that the method can be used for comparing different machines, and screening out more destructive machines from sensitive sites. For example, 8-wheeled forwarder seems less destructive, even the difference has less practical meaning.

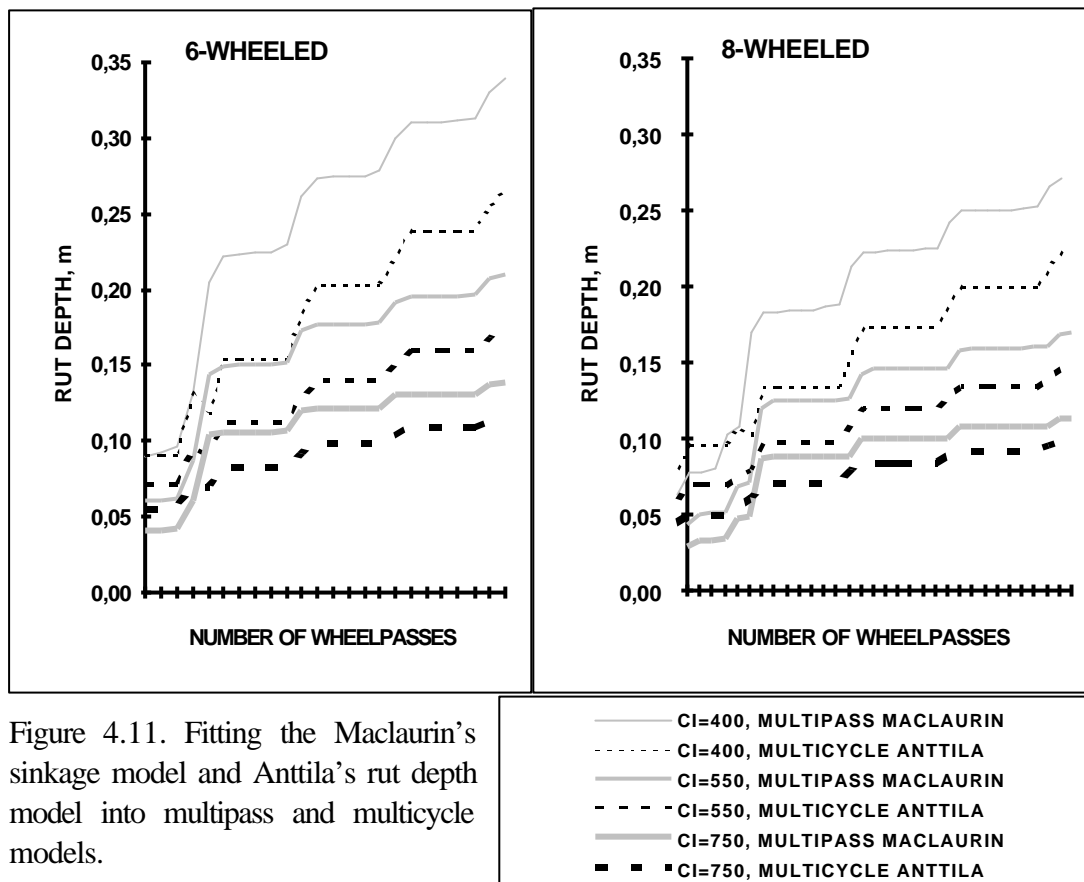


Figure 4.11. Fitting the Maclaurin's sinkage model and Anttila's rut depth model into multipass and multicycle models.

Four different multipass/multicycle models are compared in Figure 4.11. Used sinkage and rut depth models are the following: Dwyer, models Eq.(3.20) and (4.20), Turnage Eq.(4.19), Anttila, Eq.(4.5, Model 5) and (4.24) and Rummukainen Eq.(4.8) and (4.27).

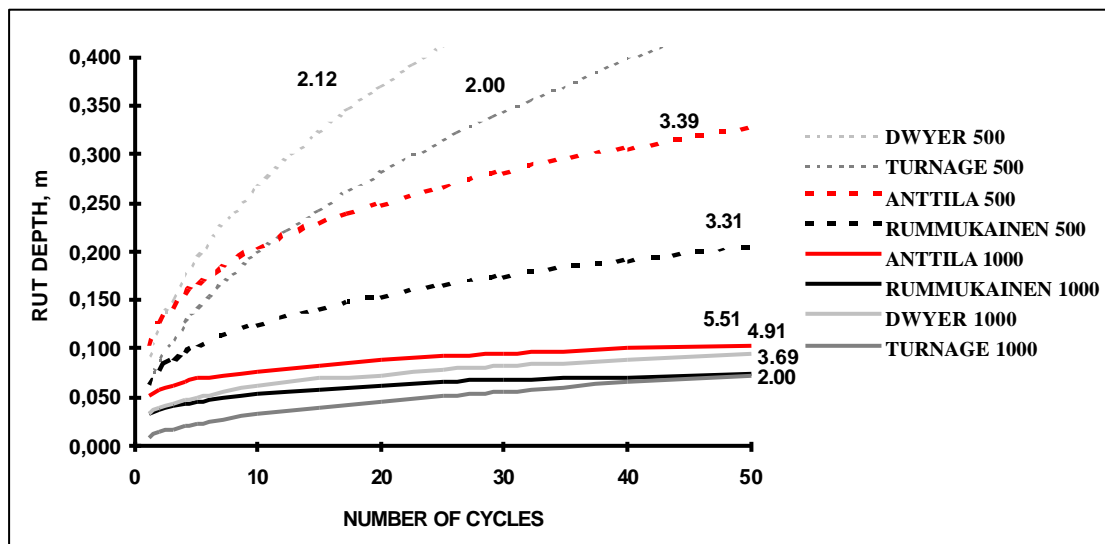


Figure 4.12. Comparison of calculated rut depth as a function of number of cycles on two soils,

CI =500 and 1000 kPa using four different models to estimate the multipass coefficient (numbers attached to each curve).

From Figure 4.11 it can be seen, that results are rather close to each others, specially taking into account the large variation in real terrain tests on sensitive sites, close to the trafficability limit. No model gives a change to work continuously on site with 500 CI-class, and practically all models give rut depth over 100 mm for already for the first pass. All the models permit continuous work on 1000 CI-class, because the rut depth after 50 pass stays still under 100 mm.

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